A better approximation to the modelling of the Sachs-Wolfe effect

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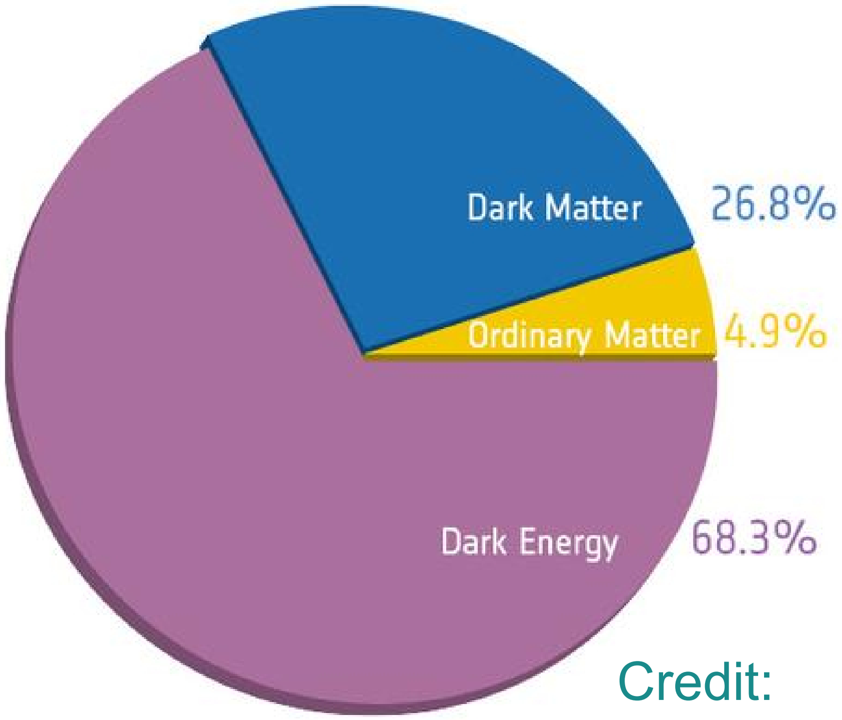
The Lambda-CDM model

The concordance model Lambda-CDM

- Universe originates from a high density state and expands according to FLRW Universe model.
- It contains dark energy, which is believed to cause accelerated expansion at present time.

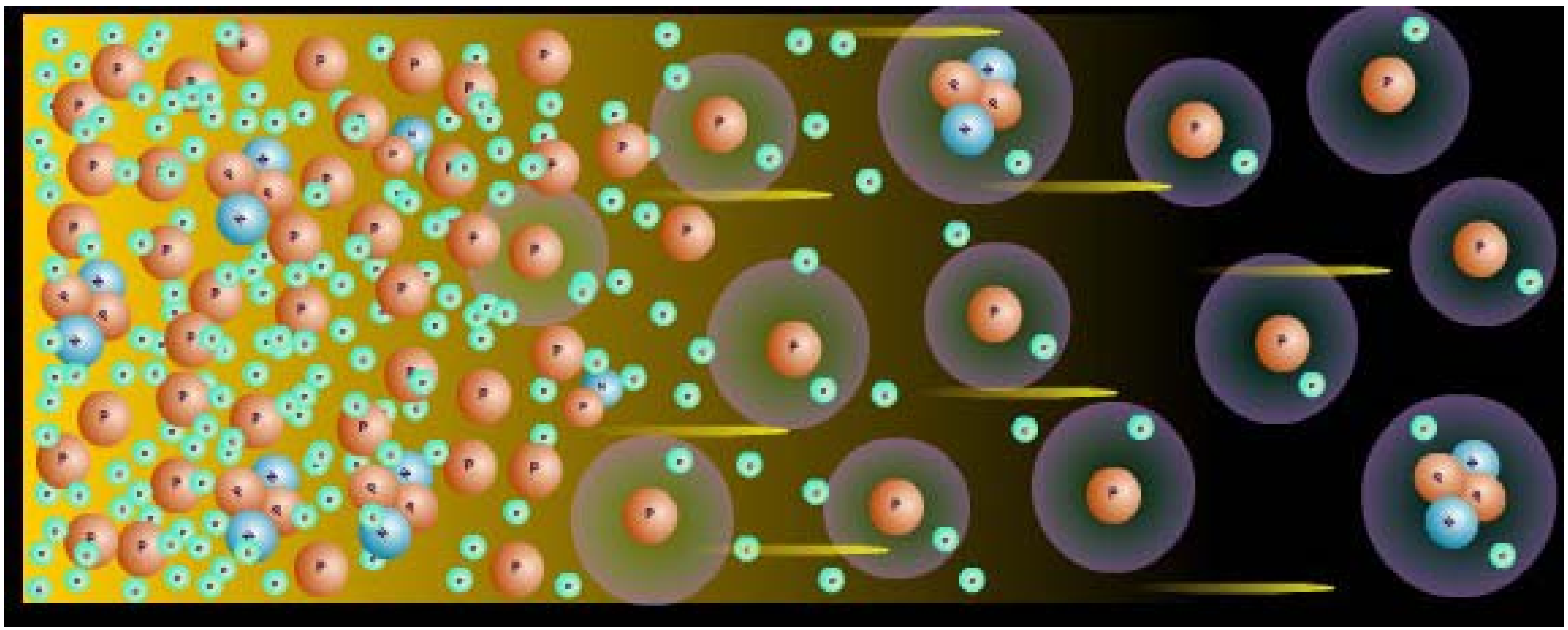


Credit: ESA/Planck

Actual composition of the Universe by species.

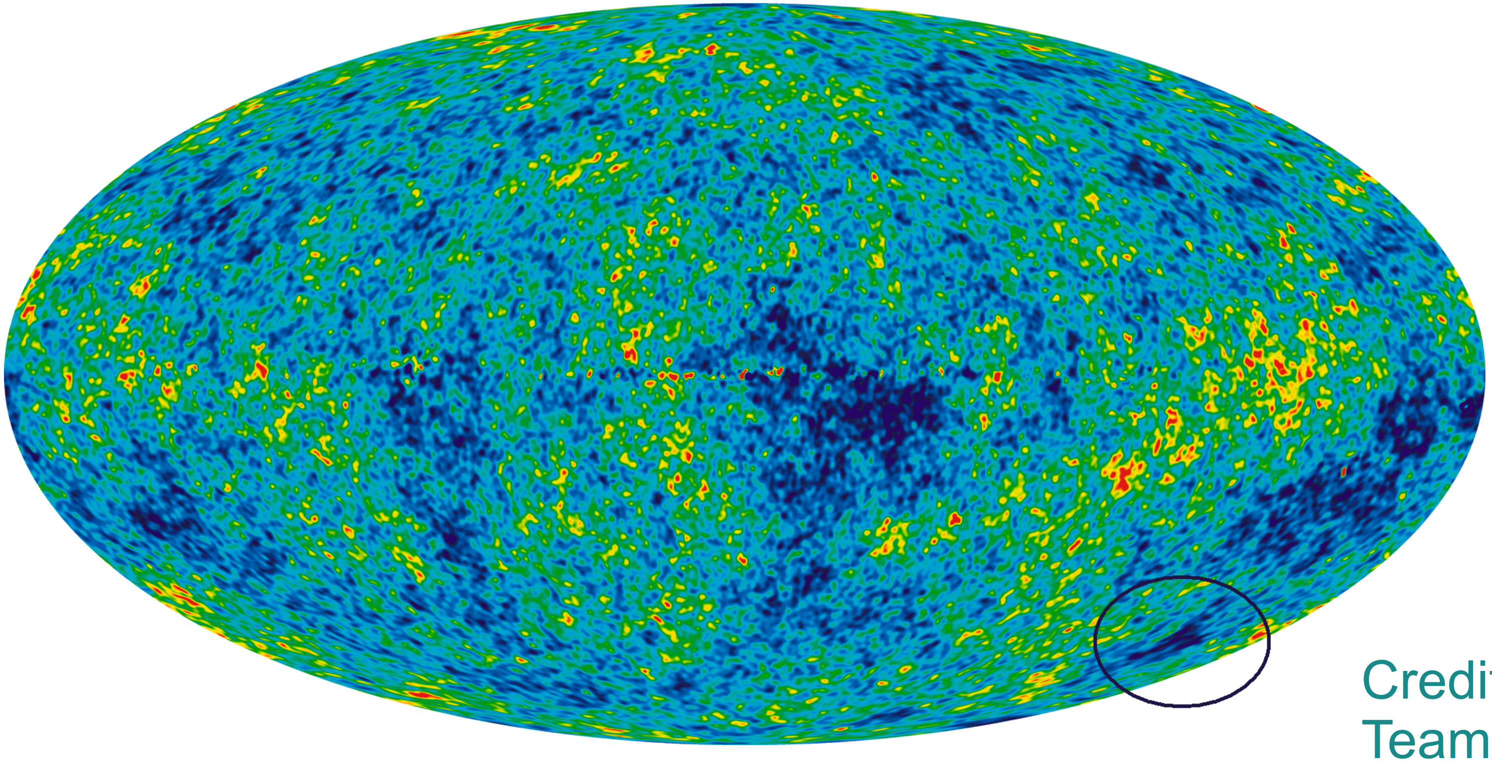
The Cosmic Microwave Background

Time



As the high density Universe expands, light decouple from ordinary matter at 380,000 years since the Big-Bang

Anisotropies in the CMB temperature

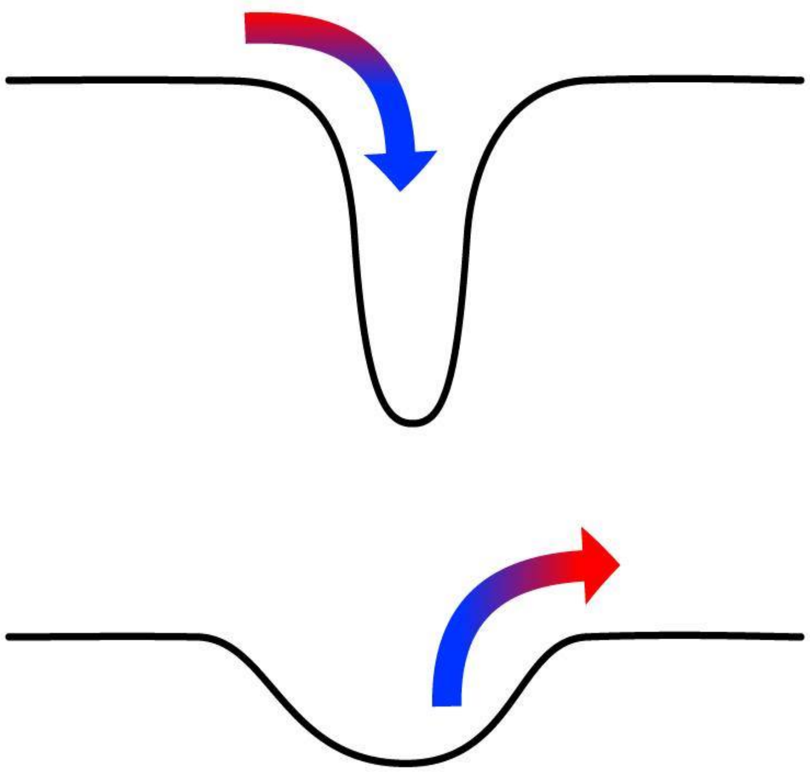


Credit: WMAP Team, NASA

Cold spot in the CMB. Recent studies show a supervoid may be the cause of it.

(I. Szapudi, et. al., MNRAS, 2015)

Secondary temperature anisotropies: the Sachs-Wolfe effect



Photon entering an overdensity gets blueshifted (top). When going out it gets redshifted (bottom). Expansion of the perturbation potential induces a net gain in energy.

(R. Sachs, A. Wolfe, ApJ, 1968)

Does the discrepance in the calculation of the ISW comes from the approximations made?

(P. Pápai et. al., ApJ, 2011)

(T. Giannantonio et. al., MNRAS, 2012)

(U. Sawangwit, MNRAS, 2010)

(S. Nadathur et. al., JCAP, 2012)

The theoretical approach

Perturbed FLRW spacetime: the conformal newtonian gauge

- Allows to explain the evolution of the Universe perturbations.
- General Relativity implies gravitational redshift contributions from potential of density perturbations (ϕ).
- Photons move radially in a perturbation in a path with line element:

$$ds^2 = -\left(1 + \frac{2\phi}{c^2}\right)(dx^0)^2 + a^2(t)\left(1 - \frac{2\phi}{c^2}\right)dr^2$$

Perturbed FLRW spacetime: the conformal newtonian gauge

- Full geodesic equations for a radially moving photon in a perturbed FLRW spacetime:

$$\ddot{x}^0 + \frac{2\dot{x}^0}{c^2}\left(1+\frac{2\phi}{c^2}\right)^{-1}\left(\frac{1}{c}\phi_{,t}\,\dot{x}^0 + \phi_{,r}\,\dot{r}\right) - \frac{\phi_{,t}}{c^3}\left[\left(\dot{x}^0\right)^2 + a^2\dot{r}^2\right]$$
$$+\left(1-\frac{2\phi}{c^2}\right)\left(1+\frac{2\phi}{c^2}\right)^{-1}\frac{aa'}{c}\dot{r}^2 = 0$$

Equation for temporal component of photon's path

$$\ddot{r} + \frac{2a'}{ca}\dot{x}^0\dot{r} - \frac{2\phi_{,t}}{c^3}\left(1-\frac{2\phi}{c^2}\right)^{-1}\dot{x}^0\dot{r} + \frac{\phi_{,r}}{a^2c^2}\left(1-\frac{2\phi}{c^2}\right)^{-1}\left(\dot{x}^0\right)^2$$
$$-\frac{\phi_{,r}}{c^2}\left(1-\frac{2\phi}{c^2}\right)^{-1}\dot{r}^2 = 0$$

Equation for radial component of photon's path

Evolution of density perturbations: dark matter halos

Gravitational potential of a dark matter halo can be simulated by a Hernquist sphere, which has potential:

$$\phi(r, z) = -\frac{GM(z)}{r+a}$$

Distance parameter

(L. Hernquist, Apj, 1990)

Temporal evolution of the dark matter halo mass is given by

Evolution parameters

$$M(z) = M_0(z+1)^\beta e^{-\gamma z}$$

(S. Sanes, 2011)

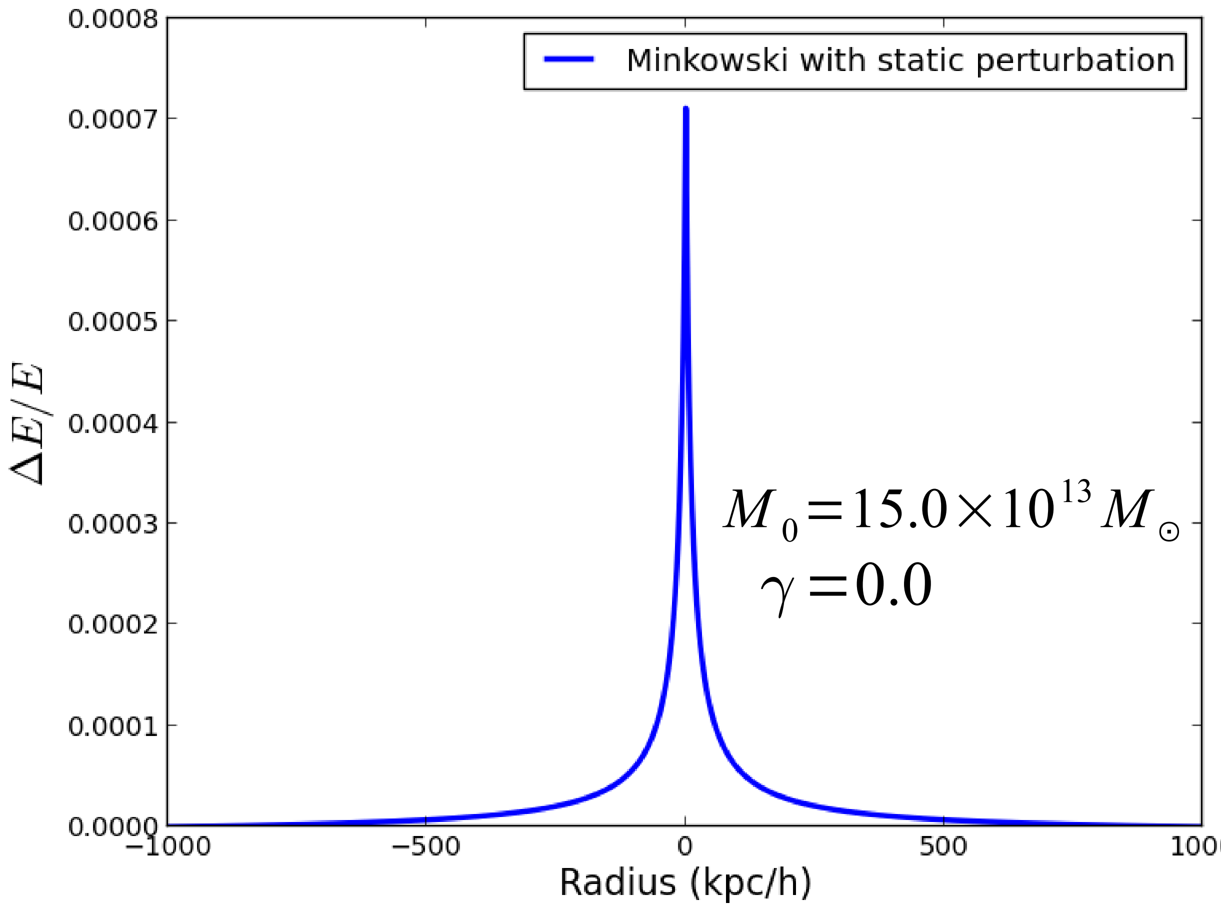
Mass at present time

β can always be taken to zero!

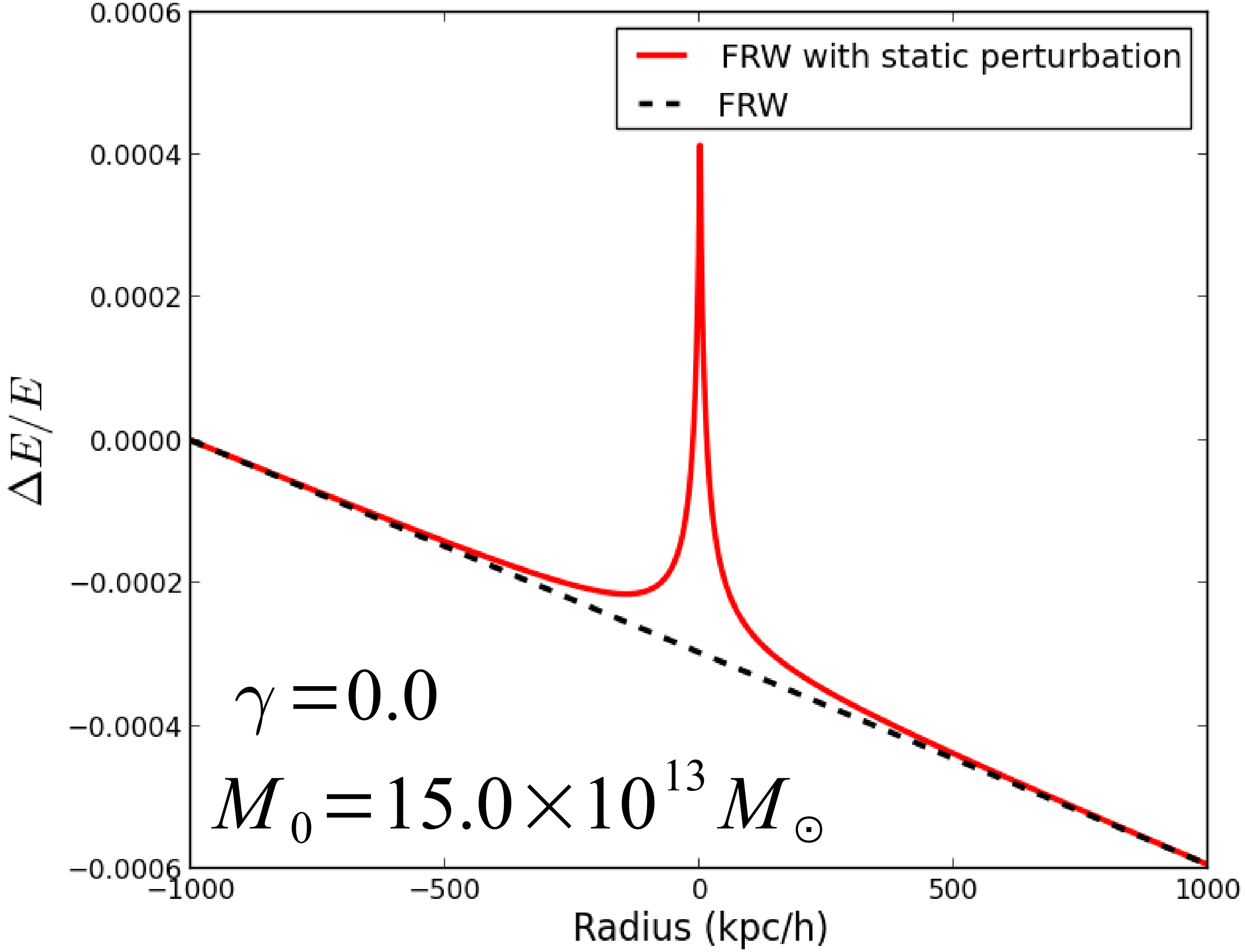
Numerical simulation results

Case: Minkowski + static perturbation

Fractional energy change vs. radius. Geodesic equations solved with RK4. Net energy change in photon's energy is zero as expected.

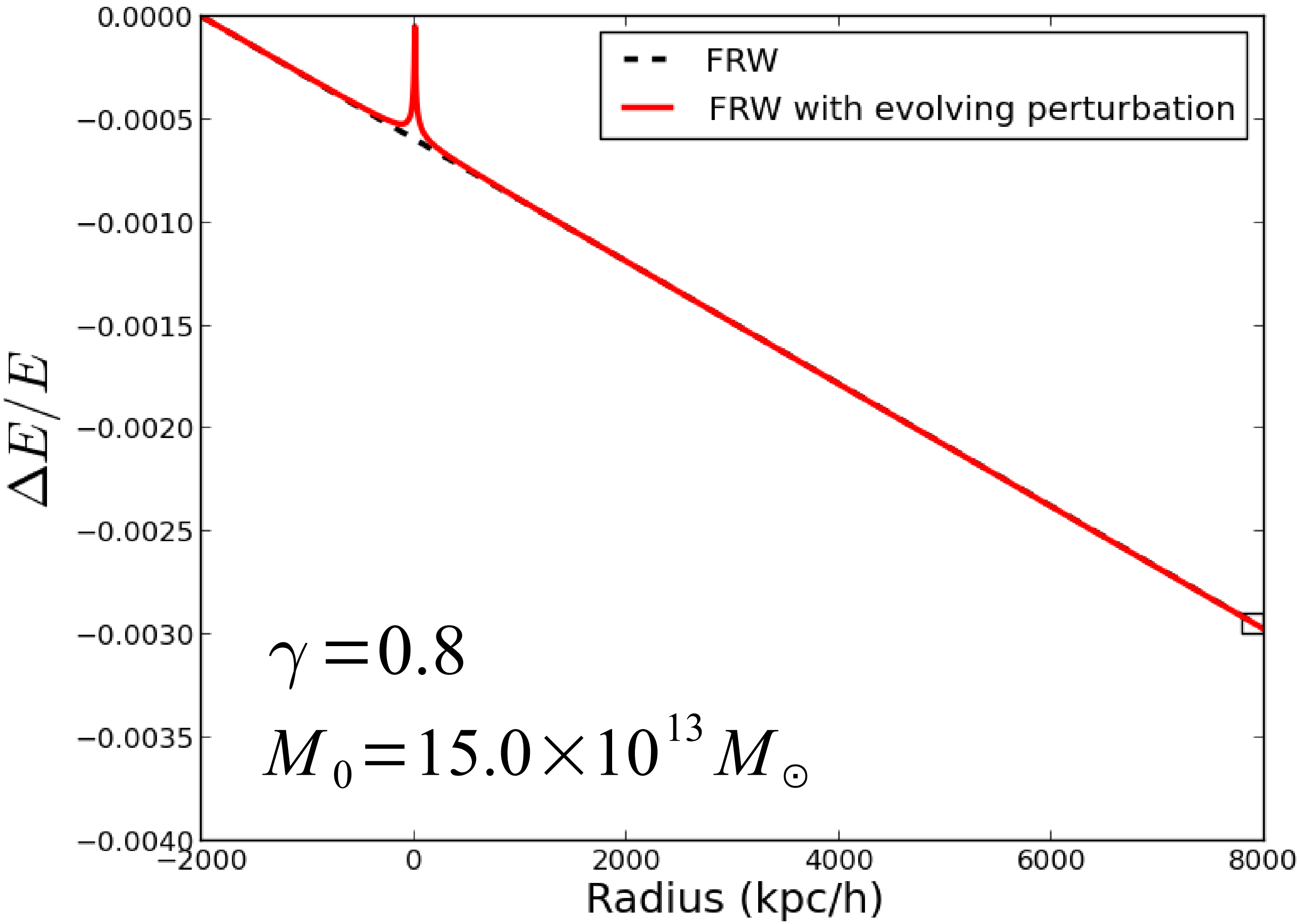


Case: FLRW + static perturbation



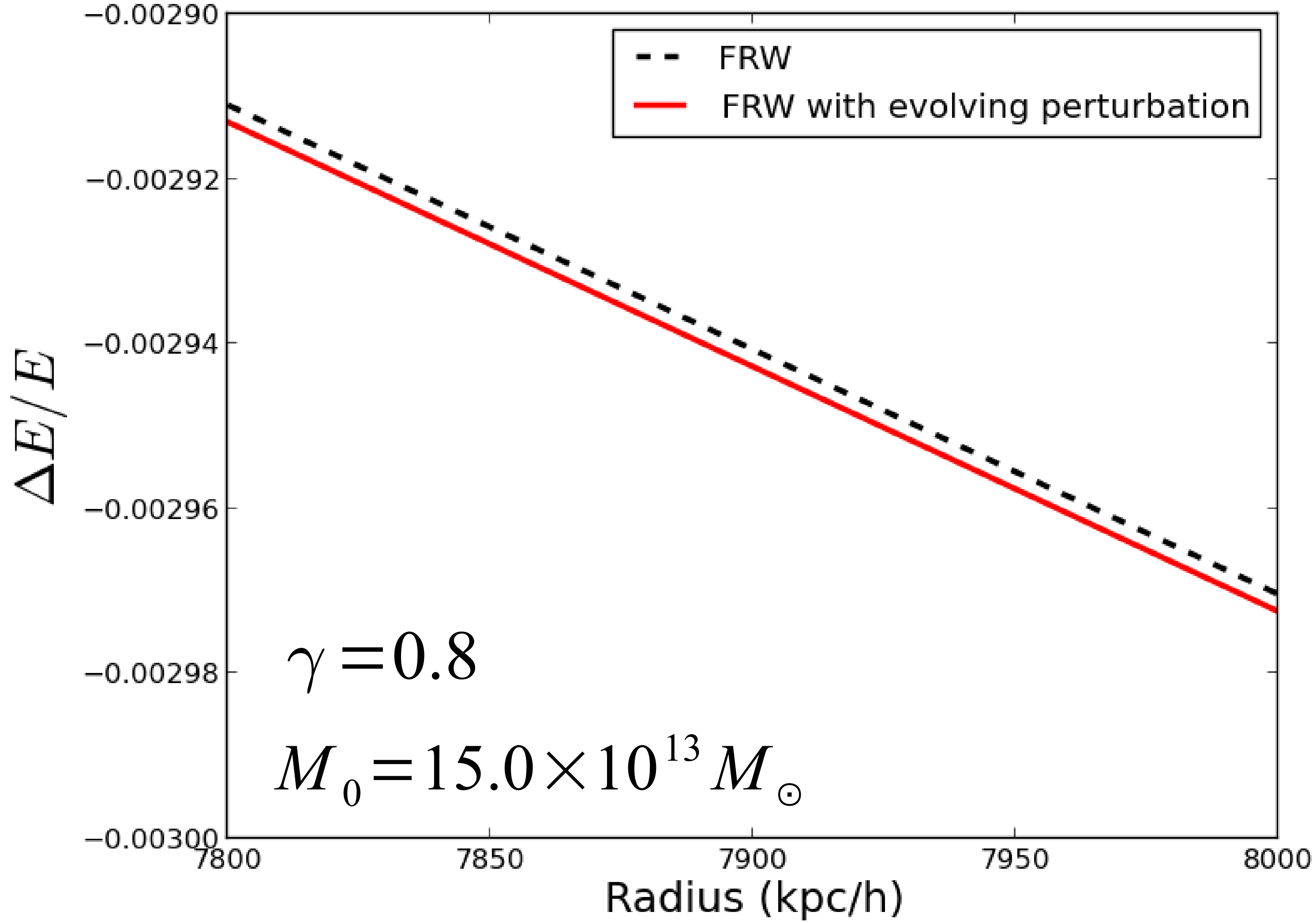
Fractional energy change vs. radius: net energy gain is zero.

Case: FLRW + evolving perturbation (ISW effect)



Zooming in to a little region far away the perturbation

Case: FLRW + evolving perturbation (ISW effect)



Net energy lose for a photon!

$|\Delta T/T| = 6.4 \times 10^{-6}$

Conclusions

- Realistic evolving dark matter halos can produce temperature fluctuations in the CMB of $|\Delta T/T| = 6.4\times10^{-6}$.
- We have shown more accurate and realistic simulations for gravitational effects can be done. These simulations are needed as we are entering in the precision era of Cosmology.

Thanks for your attention!